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The PHELIX Pulsed Power Project: Bringing Portable Magnetic Drive Proton Radiography

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Abstract

The PHELIX pulsed power project will introduce magnetically driven hydrodynamics experiments to the Los Alamos National Laboratory's proton radiography facility (pRad). The Precision High Energy-density Liner Implosion eXperiment (PHELIX) has been commissioned at Los Alamos. A small footprint capacitor bank consisting of four parallel, air-insulated, single-stage, Marx units (U ~ 300 kJ) is cable coupled to a toroidal, current step-up transformer to deliver multi-Mega-Ampere current pulses (T_{pulse} ~10 μs) to cm size cylindrical loads. In a sequence of tests the performance of each component (capacitor bank and transformer) was evaluated and compared to a computer model. The transformer coupling was observed to be k ~ 0.93. A series of liner implosion experiments has been performed in which an aluminum liner (R ~3 cm, r = 0.8 mm, L = 3 cm) was accelerated to a velocity of ~ 1 km/s. The suite of machine diagnostics included linear Rogowski coils and Faraday rotation for current measurements. The experimental diagnostics include B-dot probes, multi-channel photon Doppler velocimetry (PDV), and single-frame, and flash X-radiography to evaluate the performance of the high precision liner implosion. Currently, work is focused on integrating PHELIX into normal operations with the 800 MeV proton radiography facility at the Los Alamos Neutron Science Center (LANSCE). There, high-resolution, high-frame-rate imaging of hydrodynamic experiments will be possible.

LANL's Proton Radiography Facility

In addition to scattering and nuclear experiments, the Los Alamos Neutron Science Center (LANSCE) is home to a world-class proton radiography (pRad) facility. It is utilizes the 800 MeV proton beam as a diagnostic probe of dynamic experiment. It operates on a six month run cycle each year. Over the course of the past thirteen years, more than 500 dynamic experiments have been imaged at the facility. Figure 1 shows a photo of the inside of the proton radiography facility.

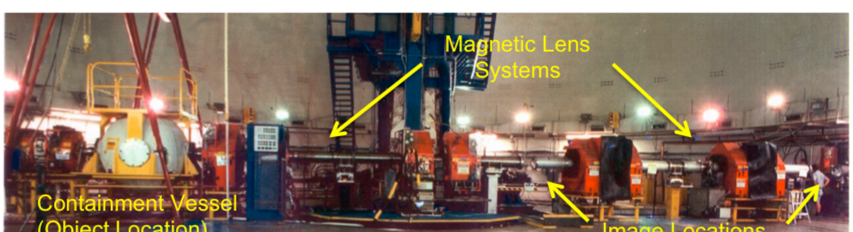

Figure 1. The LANL proton radiography facility at LANSCE. The beam enters from the left, interacts with the object in the containment vessel, and is focused my magnetic lens to two image locations.

LANL pRad is a very high resolution diagnostic. The dynamic range has been shown to be 1-70 g/cm2 as measured in iron. The spatial resolution is ~65 μm FWHM Gaussian for double-line calibration. Temporal varies depending on the target. An image is built up by gating individual 5 ns proton packets. 60-100 ns exposure is typical. A movie of 10-30 images is custom tailored to the dynamics of the experiment. There are several other considerations in calculating the expected transmission and resolution of a particular experiment. Here we only mention the effects like detector blur, chromatic aberration, and limbing[1].

As mentioned above, over 500 dynamic experiments have been performed at pRad. It is worth giving an example. Here approximate-planer geometry it utilized. A disk of high explosive (HE) imparts a shock into different targets. It should be pointed out that the strength of the shock is determined by the particular composition of the HE. One advantage of magnetic, pulsed-power drive is that the drive strength can be continuously varied within a range, by the setting the voltage to which the capacitor bank is charged.

An example of a dynamic material experiment imaged with pRad is the comparison of the spall of various ductile materials. Here a disk is subject to a strong shock. The rarefaction waves meet within the material and put it into such extreme tension that failure occurs and the sample "spalls." Figure 2 shows the pRad images of the spall of various materials. The shock is incident from the bottom into a target disk. In each case a spall scab has dethatched from the sample and is traveling upward away from it.

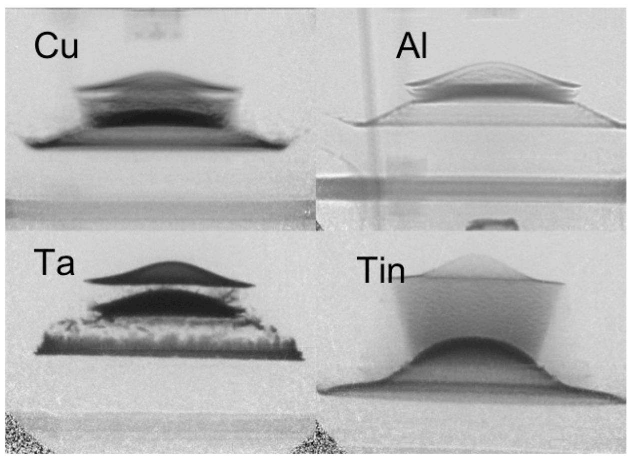

Figure 2. pRad imaging of the spall of various materials.

PHELIX – Precision High Energy-density Liner Implosion Experiment

In order to provide a driver complementary to HE at pRad, the PHELIX portable pulsed-power driver has been designed and is being constructed. In addition to being able to drive continuum size samples, the main requirement is that it be small and mobile. The whole system has to fit into a 200 ft^2 platform in order to be used at the pRad facility.

It should be pointed out that a pulsed-power driver has several desirable features for dynamic materials experiments. It is naturally cylindrical, which reduces the edge effects in at least one dimension. Since the magnetic field is mass-less and is dissipated by Joule heating, there is no residual stored energy, and thus less chance of collateral damage. As mentioned before, the drive strength is dial-able via the charge voltage of the capacitor bank. Indeed, a small, portable pulsed-power driver at the multi-frame pRad facility has a distinct economic advantage in rate of data return over a fixed location bank, where only a few frames of imaging can be obtained in a single experiment. Figure 3 shows the conceptual use of pRad to diagnose a pulsed-power driven, liner-on-target experiment.

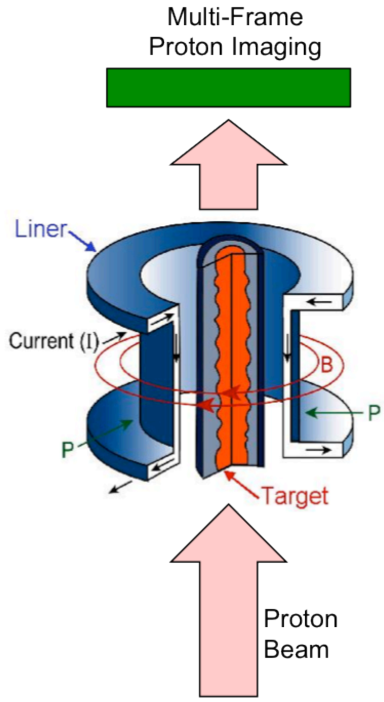

Figure 3. Conceptual use of proton radiography in a pulsed-power, liner-on-target experiment.

The key components and technology of PHELIX are as follows. A two-module, 68 μF, 120 kV, air-insulated marx-modules are cable coupled to a toroidal current step-up transformer[2,3]. It has a 4:1 winding ratio and a magnetic flux coupling efficiency of k = 0.93. The secondary winding and experimental load has very low inductance. Thus 1 MA peak current in the primary winding produces 4 MA peak current in the secondary winding for driving a liner. In order to not produce too much reverse voltage on the capacitors, reticulated vitreous carbon damping resistors are used on the output headers of each module for a total of 25.1 mΩ of resistance.

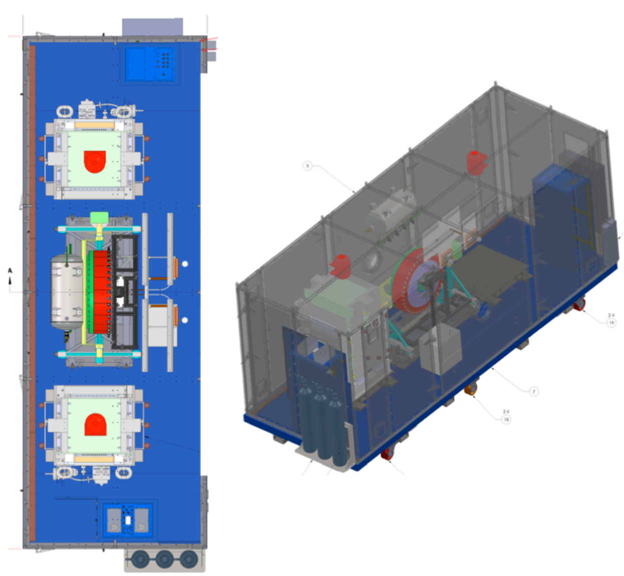

Figure 4. The PHELIX portable pulsed-power driver on a 8' x 25' platform. Two marx modules bracket the toroidal tranformer.

The PHELIX marx-module, transformer, load system has been extensively tested in the laboratory. The first step was to commission the marx modules. For this a set of 1 m long, shorted cables was attached to each bank. Current viewing transformers and linear Rogowski coils measured the current. The result was a pulse with ~1.5 MA peak current and 6 μs width.

The next step in testing was to connect the marx modules to the transformer and install a static load of 1 nH. A series of shots at voltages 50-84 kV was conducted. Faraday Rotation measured the current in the secondary winding. Figure 5 shows the measured secondary winding current for the 50 kV shot. A peak current of 3 MA and pulse width of 10 μs is observed. The series showed linear dependence of peak current on charge voltage.

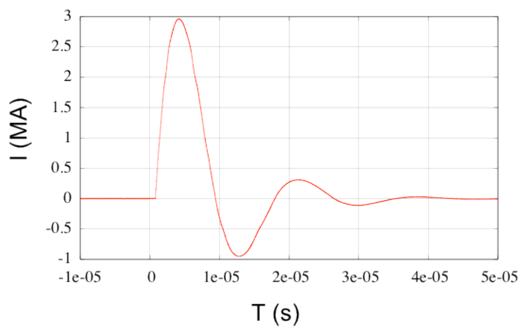

Figure 5. Secondary winding current for the transformer with static load and bank voltage of 50 kV.

The final test of PHELIX was a dynamic liner implosion experiment. Figure 6 shows a cutaway of the liner cassette. The blue piece is a central measuring unit (CMU) with 12 channels of photon Doppler velocimetry (PDV) of the inner surface of the liner. In orange are the heavy copper glide planes. In green is the aluminum return conductor. The inner surface of the liner is in grey. It is only 0.8 mm thick with 3 cm between the glide planes.

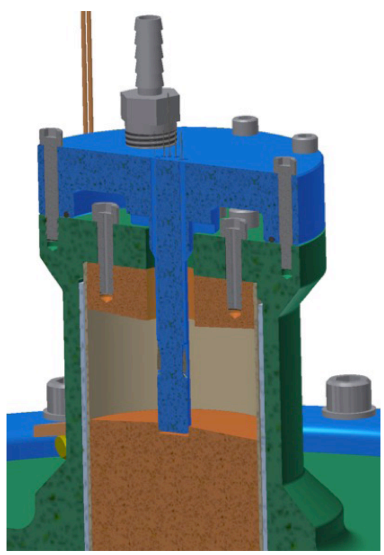

Figure 6. Cutaway of the PHELIX dynamic liner experiment.

A single frame of flash X-radiography captures both the static cassette as well as the dynamic implosion in Figure 7. The liner displays a high degree of both axial and azimuthal symmetry.

The PDV confirms the symmetry. The 12 channels were arrayed at three axial stations (2 at +10 mm from the mid-plane, 2 at -10 mm from the mid-plane, and 8 in the mid-plane). Figure 8 shows the results of the PDV measurements. They show that the liner achieved > 1 km/s velocity.

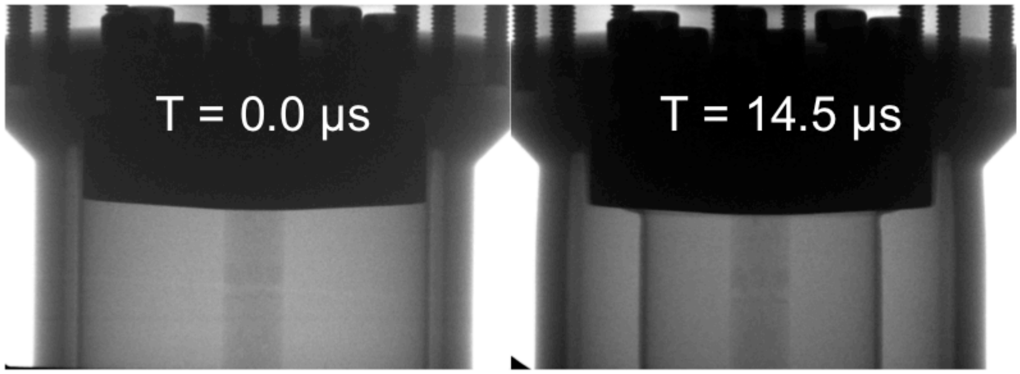

Figure 7. Flash X-Radiography of the PHELIX liner implosion experiment. The static is on left and the dynamic is on the right.

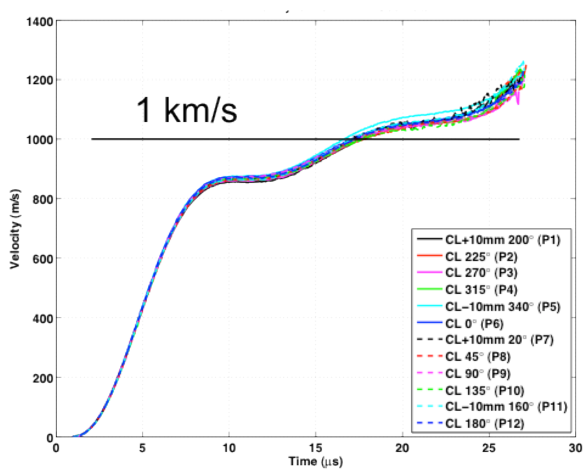

Figure 8. Plot of the 12 Channels of PDV looking at the inside of the liner.

Summary

The LANL proton radiography facility with its 800 MeV beam, ~50-100 μm spatial resolution and high frame-rate imaging has conducted over 500 dynamic experiments over its thirteen year history. The PHELIX portable pulsed power machine will expand the capability of dynamic materials experiments that can be fielded. The first-of-its-kind transformer technology has been tested in the laboratory. A dynamic liner experiment produced a 4 MA peak current with a 10 μs pulse width. The liner was accelerated to > 1 km/s velocity. Flash radiography and multichannel PDV showed a high degree of symmetry.

References

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[3] P. J. Turchi et al., *IEEE Trans. Plasma Sci.*, **39**, 2006-2013, 2011.